

X-ray Emission of Supernova 1998bw in the Error Box of GRB980425

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The spatial and temporal coincidence of a GRB and a supernova explosion (1998bw) on 25 April 1998 has raised conjectures on the physical connection between the two phenomena, and in general on the association of GRBs with supernovae, at least with the most powerful among them (hypernovae or collapsars). In fact, multiwavelength observations of SN 1998bw have revealed unusual characteristics: extremely high energy output at radio and optical wavelengths, and relativistic expansion of the outgoing shock. The X-ray emission of SN 1998bw, monitored by BeppoSAX starting ~ 10 hours after the GRB detection, was remarkably prompt (within one day of supernova detonation), but exhibited spectral and temporal properties similar to those of other supernovae detected in X-rays.

1. Introduction

The discovery of a supernova within the $8'$ radius error circle of the GRB980425 has been regarded as a major puzzle within the thick mystery of GRBs. The GRB980425, which has been detected by the BeppoSAX Gamma Ray Burst Monitor (GRBM, 40-700 keV) and by BATSE (Kippen 1998), and rapidly localized by the BeppoSAX Wide Field Cameras (WFC, 2-26 keV) Unit 2, appears as a relatively weak burst, characterized by a single, non structured peak of longer duration in the 2-26 keV range (52 seconds) than in the 40-700 keV range (31 seconds). In Figure 1 (left panel) are reported the temporal profiles in both energy ranges. The spectrum of the GRB rapidly softens with time (Figure 1, right panel; see also Frontera et al. 1999).

Weak intensity, a single peak, a soft and fastly evolving spectrum, and a ~ 5 second temporal delay of the X-rays with respect to the γ -rays appear to be the main characteristics of this GRB. However, these features are common to other GRBs, and therefore cannot be considered as an obvious suggestion that GRB980425 is peculiar.

It came as a surprise for the teams involved in GRB search and follow-up at longer wavelengths, and subsequently for the whole astronomical community, that in the error box of GRB980425 a supernova was detected, 1998bw, at the optical (Galama et al. 1998; Galama et al. 1999a), and radio wavelengths (Kulkarni et al. 1998a), 17 hours and 3 days after the GRB event, respectively. The inferred time of supernova explosion is consistent with the GRB occurrence to within $+0.7/-2$ days (Iwamoto et al. 1998).

SN 1998bw lies in a spiral arm of the galaxy ESO 184-G82, at a redshift $z = 0.0085$ (Tinney et al. 1998). Its radio luminosity ($\sim 10^{38}$ erg s⁻¹ at peak) is the largest ever measured for any supernova, and the optical one ($\sim 10^{43}$ erg s⁻¹ at peak) ranks among the highest supernova luminosities.

SN 1998bw stands out not only for its positional and temporal coincidence with GRB980425 and for its unusual radio and optical luminosity, but also for the properties of the radio light curves (Kulkarni et al. 1998a; Wieringa et al. 1999) and for the broad optical spectral lines, which indicate high photospheric velocities. Based on its optical spectrum, SN 1998bw was classified as a peculiar Type Ib before maximum light (Sadler et al. 1998) and Type Ic at later epochs (Iwamoto et al. 1998; Galama et al. 1998; Patat & Piemonte 1998).

2. BeppoSAX Target of Opportunity Observations of the GRB980425 Error Box

Following the GRB event, the field of GRB980425 was promptly acquired by the BeppoSAX Narrow Field Instruments (NFI; these include the LECS, MECS, HPGSPC, and PDS detectors. See Butler & Scarsi 1990, and Boella et al. 1997 for a description of the BeppoSAX mission), and observations in the energy range 0.1-300 keV started 10 hours after the GRB detection (26-27 April 1998). Two previously unknown sources have been detected within the WFC error box by the MECS in the 2-10 keV energy range (Pian et al. 1999a; Pian et al. 1999b).

The brighter source, S1, is consistent with the position of SN 1998bw, while the fainter one, S2, is not (Figure 2). The LECS data have a significantly lower signal-to-noise ratio than the MECS data and the HPGSPC and PDS instruments yielded no detection above the background, therefore we will briefly report here only the MECS results and refer to a paper of imminent submission for details about both LECS and MECS data (Pian et al. 1999b).

Note that the coordinates of sources S1 and S2 distributed by Pian et al. (1998) have been revised in November 1998, to take into account a systematic error due to the non-optimal spacecraft attitude during the April and May 1998 observations (see Piro et al. 1998a). Figure 2 illustrates the updated, correct location of the sources.

The following NFI pointings, one week (2-3 May 1998) and six months later (10-12 November 1998), have shown that neither source exhibits the behavior expected for an X-ray afterglow. Source S1 did not exhibit significant variability in one week, and was still detected, a factor of ~ 2 fainter, six months later (see Figure 3). Source S2 exhibits marginally significant variability between 26-28 April and 2-3 May 1998. It is not detected in November 1998, but its upper limit is consistent with the April-May flux level (see Figures 3 and 4a).

The variability of source S1 and its positional consistency with SN 1998bw suggest that S1 is the X-ray counterpart of the supernova. This is the earliest detection of X-ray supernova emission, and the first detection of medium energy X-rays from a Type I supernova (the only other case of X-ray bright supernova is the Type Ic SN 1994I, detected in the soft X-rays by ROSAT, Immler et al. 1998a).

At the distance of SN 1998bw, the luminosity observed in the range 2-10 keV, $\sim 2.5 \times 10^{40}$ erg s $^{-1}$, is compatible with that of other supernovae detected in the same energy band, all Type II (see Table 1). However, the supernova X-ray luminosity could suffer from host galaxy contamination, which might be significant at these energies (see Fabiano 1989). Similarly, the observed variation of a factor of two in six months is only a lower limit to the supernova X-ray variability amplitude. A power-law $f(t) \propto t^{-p}$ with index $p \sim 0.2$ provides an acceptable fit of the light curve (Fig. 4b), and is approximately consistent with the behavior observed for other supernovae (Kohmura et al. 1994; Houck et al. 1998) and with predictions based on interaction of energetic electrons with the circumstellar medium (Chevalier & Fransson 1994; Li & Chevalier 1999).

The prompt X-ray emission observed for SN 1998bw requires that the circumstellar medium is highly ionized (probably by the powerful explosion), to allow the X-rays to escape so soon after the explosion (see Zimmermann et al. 1994), and also very dense, as inferred also from the large radio output (Kulkarni et al. 1998a; Wieringa et al. 1999).

The spectrum of S1 in the 2-10 keV energy range is well fitted by a power-law $F_\nu \propto \nu^{-\alpha}$ of index $\alpha = 0.5 \pm 0.2$ (1- σ), or by a thermal bremsstrahlung model with temperature ~ 15 keV (see Pian et al. 1999b for details on the spectral fits). Both are consistent with

spectral slopes and temperatures found for other supernovae detected in X-rays (e.g., Kohmura et al. 1994; Leising et al. 1994; Dotani et al. 1987).

The mildly relativistic conditions of the expanding shock of SN 1998bw (Kulkarni et al. 1998a) might suggest that the mechanism responsible for the X-ray emission is synchrotron radiation of very energetic electrons, or inverse Compton scattering of relativistic electrons (which produce the radio spectrum via synchrotron) off optical/UV photons of the thermal ejecta. The X-ray spectral index is consistent with that measured for the radio spectrum starting ~ 15 days after the explosion (Kulkarni et al. 1998a; Wieringa et al. 1999; before that epoch the radio spectrum is significantly self-absorbed), and with the spectral slope connecting quasi-simultaneous radio and X-ray measurements ($\alpha \sim 0.8$). Therefore, in case the X-rays have a non-thermal origin, it is difficult to establish whether they are produced through the synchrotron or inverse Compton process (Fig. 5).

3. The GRB/Supernova Connection

Although the chance coincidence of GRB980425 and SN 1998bw has a very low probability (10^{-4} , Galama et al. 1998), the GRB community has not accepted unanimously the physical association of the GRB and the supernova. In fact, the faint source S2 - possibly, but not clearly, fading - could be considered an afterglow candidate. The flux of S2 during the first BeppoSAX observation would be consistent with a power-law decay of index $p \simeq 1.3$ after the early X-ray emission observed by the WFC (see Fig. 4a). This is in the range of the power-law decay indices of “classical” X-ray afterglows (Costa et al. 1997; Nicastro et al. 1998; Dal Fiume et al. 1999; in ‘t Zand et al. 1998; Nicastro et al. 1999; Vreeswijk et al. 1999a; Heise et al. 1999). However, the second detection of S2 is not conclusive: it is marginally consistent with the first detection, but it is also marginally consistent with the power-law decay. The November 1998 upper limit is consistent with the detection level. Therefore, based on the present data, one cannot establish whether S2 is an afterglow exhibiting a small re-bursting (similar to GRB970508, although the time scale would be different, Piro et al. 1998b) or a permanent, perhaps modestly variable, X-ray emitter, like an active galactic nucleus or a Galactic binary (the chance probability of detecting a source of the level of S2 in the $8'$ radius WFC error box of GRB980425 is rather high, $\sim 12\%$). Optical observations have been equally inconclusive: no optical transient at a position consistent with S2 has been detected by early imaging of the GRB error box, and late epoch optical spectroscopy of sources brighter than $V \sim 18$ in the S2 error box failed to identify any active galaxy or binary stellar system having a compact object (Halpern 1998, and private communication).

At the time of GRB980425/SN 1998bw detection, five optical afterglows of GRBs had been detected, and for all of them, similarly to X-ray afterglows, a rapid power-law decay had been measured with index p in the range 1.1-2.1 (Van Paradijs et al. 1997; Fruchter et al. 1999a; Fruchter et al. 1999b, and references therein; Diercks et al. 1998; Halpern et al. 1998; Kulkarni et al. 1998b; Groot et al. 1998; Palazzi et al. 1998). The circumstance of detecting a supernova as the possible counterpart of a GRB was unprecedented. Therefore, it was proposed that this GRB might belong to a different class of events, with apparently indistinguishable high energy characteristics, but with different progenitors. Furthermore, assuming association with SN 1998bw, GRB980425 would be much closer than the GRBs for which a redshift measurement is available, which reinforced the idea that GRB980425 was physically dissimilar from GRBs exhibiting power-law decaying X-ray and optical remnants, predicted by the cosmological fireball model (Rees & Mészáros 1992; Piran 1999).

After the case of GRB980425/SN 1998bw, many authors have searched for statistical support of the possible association between GRBs and supernovae, and obtained different, and sometimes conflicting, results. The comparison of the BATSE catalog with supernovae compilations seems to suggest that some GRBs may be spatially (within an angular uncertainty of many degrees) and temporally (within ~ 20 -30 days) consistent with Type Ib/c supernovae, while association with Type Ia is ruled out (Wang & Wheeler 1998. See however Kippen et al. 1998 and Graziani et al. 1998). Association has been specifically proposed for the cases of the Type II supernovae 1997cy and 1999E with GRB970514 and GRB980910, respectively, based on temporal and spatial proximity and on the outstanding optical properties of the two supernovae (Woosley et al. 1999; Germany et al. 1999; Thorsett & Hogg 1999; Turatto et al. 1999). However, limiting the GRB sample to the events with temporal profile similar to GRB980425 leads to no significant association (Bloom et al. 1998a). A negative result is also obtained by further restricting the subset to long, soft GRBs (Norris et al. 1998). This seems to suggest that the temporal and spectral characteristics of GRBs are not obvious tracers of possible association with supernovae.

More recent studies have shown that the optical afterglows of some GRBs exhibit deviations from a “pure” power-law decay, and these have been ascribed to the possible presence of a supernova underlying the afterglow (GRB970228, Reichart 1999; Galama et al. 1999b; GRB970508, Germany et al. 1999; GRB980326, Bloom et al. 1999; GRB990510, Fruchter et al. 1999c; Beuermann et al. 1999; GRB990712, Hjorth et al. 1999). This makes the association between GRB980425 and SN 1998bw more solid, and supports the speculation that all GRBs of long duration (>1 s) are formed by extremely energetic supernova explosions (“failed” supernovae, hypernovae, or collapsars, Paczyński 1998; Woosley et al. 1999; MacFadyen & Woosley 1998). These observational hints and theoretical picture suggest that GRB980425 and some GRBs for which a counterpart has been detected at frequencies lower than the γ -rays belong to a same class and have similar progenitors, despite the different distance and behavior of the multiwavelength counterparts.

Indeed, the recent discovery of a GRB optical afterglow at the intermediate redshift $z = 0.43$ (GRB990712, Galama et al. 1999c) might support a continuity of properties between GRB980425 and the other precisely localized GRBs, perhaps based on the different amount of beaming, according to the degree of jet alignment (Eichler & Levinson 1999; Cen 1998; Postnov et al. 1999; Woosley et al. 1999). In this scenario, in highly beamed GRBs the non-thermal multiwavelength afterglow could overwhelm the underlying supernova emission. The latter should instead be detected more clearly in GRBs seen off-axis, like GRB980425, which also appear weaker. Assuming association with SN 1998bw and isotropic emission, the total energy of GRB980425 in the 40-700 keV range, $\sim 5 \times 10^{47}$ erg, is at least four order of magnitudes less than that of GRBs with known distance (see Figure 6).

4. X-ray Supernovae and Gamma-Ray Bursts

GRB980425 has become a milestone in the history of GRB research in that it provided a strong suggestion toward the determination of GRB progenitors. The BeppoSAX rapid turnaround allowed the most prompt detection ever of X-rays from a supernova, thus bringing to 10 the number of supernovae detected at these energies (barring supernova remnants). The complete list is reported in Table 1, which represents an update of Table 3 in the review by Schlegel (1995). In addition, X-ray luminosities at the discovery epoch are reported.

Since the epoch of Schlegel's review, the number of X-ray supernovae has doubled, and the detection of SN 1998bw has confirmed that medium energy X-rays are produced also from Type Ib/c supernovae. This result was predictable, given that these must have environments similar to Type II, namely a dense circumstellar medium produced by the slow wind of the progenitor, with which the supernova shock interacts producing both radio and X-ray emission.

Several issues have still to be clarified about GRB980425/SN 1998bw for what concerns X-ray emission. Particularly, an observation of the field with an instrument with good imaging angular resolution (like Chandra) is required to study in detail the host galaxy in X-rays and to disentangle it from the point-like supernova emission at the various epochs of BeppoSAX observation. A very sensitive instrument (like XMM) would instead allow a deep survey of the field of GRB980425 in medium energy X-rays, to detect the weak source S2 with a good signal-to-noise ratio, assuming it is broadly constant in the long term. (Its non detection would be perhaps more constraining toward its identification with the GRB afterglow.)

Based on the recent findings of possible supernova emission underlying the optical, power-law fading remnants of some GRBs, future research should exploit the X-ray observing facilities in search of analogous signatures in the X-ray afterglows. If GRBs are produced by supernovae, the same conditions which make detectable the afterglow, i.e. the presence of a sufficiently dense medium, should also favor the production of X-rays from the supernova. A possible past example might be the re-bursting of GRB970508 (Piro et al. 1998b), but it would imply a supernova X-ray luminosity four orders of magnitude larger than that of the most luminous X-ray supernova so far detected, 1988Z (Table 1). Therefore, the X-ray data available to date do not suggest any evidence of a supernova underlying a GRB afterglow. Clearly, more GRB localizations and observations of targets at redshifts no larger than ~ 0.1 are necessary to make a significant supernova detection affordable by the presently available X-ray instruments.

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Figure Captions

Fig. 1: Left panel: BeppoSAX WFC (top) and GRBM (bottom) light curves of GRB980425. Time is in seconds; the onset of the GRB, indicated by the zero abscissa, corresponds to 1998 April 25.9091. The typical $1\text{-}\sigma$ uncertainty associated with the individual flux points is $\sim 4 \text{ counts s}^{-1}$ for the WFC data and $\sim 40 \text{ counts s}^{-1}$ for the GRBM data. The vertical dashed lines divide the burst duration in two time intervals denoted by “A” (12 s) and “B” (40 s), over which the signal has been integrated to construct 2-700 keV spectra. These are reported in the right panel, along with the Band law fitting curves (Band et al. 1993).

Fig. 2: Digitized Sky Survey image ($16' \times 16'$) of the WFC error box of GRB980425 (large circle of radius $8'$). The left boundary of the IPN annulus is indicated as well as the error boxes of the two NFI X-ray sources (dashed circles of radius $1'.5$) and the position of the SN 1998bw. The two X-ray sources S1 (1SAXJ1935.0-5248, at the revised coordinates (J2000) $\alpha = 19^{\text{h}} 35^{\text{m}} 05.9^{\text{s}}$, $\delta = -52^{\circ} 50' 03''$) and S2 (1SAXJ1935.3-5252, at the revised coordinates $\alpha = 19^{\text{h}} 35^{\text{m}} 22.9^{\text{s}}$, $\delta = -52^{\circ} 53' 49''$), and SN 1998bw are consistent with the WFC and IPN locations. (From Galama et al. 1999a, reprinted with permission of *Astronomy & Astrophysics*.)

Fig. 3: BeppoSAX MECS images of GRB980425 in April 1998 (left) and November 1998 (right). The data have been smoothed with a Gaussian function of $1'.5$ FWHM. Source S1 is visible in the image center; source S2 is toward the South-East, at $\sim 4'$ away from S1.

Fig. 4: (a) BeppoSAX MECS light curves in the 2-10 keV band of the X-ray sources S1 (open squares) and S2 (filled circles) detected in the GRB980425 field. The WFC early measurement in the same band is also shown (star). The zero point for the abscissa is 1998 April 25.9091. Uncertainties associated with the WFC point and with the NFI measurements of S1, being equal to or smaller than the symbol size, have been omitted. The dotted line represents the power-law $f(t) \propto t^{-p}$ of index $p \simeq 1.3$ connecting the WFC measurement with the first NFI measurement of source S2. The extrapolation of the line to the time of the third observation falls below the lower bound of the S2 flux measurement but it is marginally consistent with it (the excess with respect to the power-law is $\sim 2.5\text{-}\sigma$). (b) Same as (a) for source S1 only. The fit to the temporal decay with a power-law of index ~ 0.2 is shown as a dotted line.

Fig. 5: Quasi-simultaneous radio-to-X-ray spectral energy distributions of SN 1998bw in 3-5 May (open circles) and 10-12 November 1998 (filled circles). Power-law fits to the X-ray spectra are shown along with their $1\text{-}\sigma$ confidence ranges (Pian et al. 1999b). The optical magnitudes have been transformed to fluxes according to Fukugita et al. (1995) and corrected for Galactic absorption using $A_V = 0.2$ (Schlegel et al. 1998), although Patat et al. (1999) argue in favor of a lower value. For the first epoch, the optical and radio data have been taken from Galama et al. (1998) and Kulkarni et al. (1998a), respectively. For the second epoch the optical data have been either interpolated

(bands *V* and *I*) between October 29 (McKenzie & Schaefer 1999) and November 26 (Vreeswijk et al. 1999c) measurements or extrapolated (bands *B* and *R*) using the late time exponential decay fitted to the light curves by Patat et al. (1999). The radio data are from Wieringa et al. (1999). Note that the BeppoSAX data represent the blend of the supernova and possible host galaxy emission and should then be considered upper limits on the X-ray emission of SN 1998bw. The optical supernova ejecta dominate the power output at both epochs. The radio and X-ray data could be consistent with a single radiation component.

Fig. 6: GRB energy output in the 40-700 keV range (assumed to be emitted isotropically) vs redshift. The open circle corresponds to GRB980329, for which the redshift was only estimated with arguments based on the appearance of the optical spectrum (Fruchter 1999. This value is controversial: the Keck detection of the possible host galaxy of the GRB would point to a lower redshift, Fruchter 1999, private communication. See alternatively Draine 1999). Redshift measurements are from Djorgovski et al. (1999a); Bloom et al. (1998b); Kulkarni et al. (1998b); Tinney et al. (1998); Djorgovski et al. (1999b); Djorgovski et al. (1998); Kulkarni et al. (1999); Vreeswijk et al. (1999b). The references for γ -ray fluences measured by the BeppoSAX GRBM are Frontera et al. (1998); Piro et al. (1998b); Dal Fiume et al. (1999); in 't Zand et al. (1998); Pian et al. (1999a); Costa et al. (1999); Amati et al. (1998); Feroci et al. (1999); Amati et al. (1999). Adopted values for the Hubble constant and deceleration parameter are $H_0 = 70$ km s⁻¹ Mpc⁻¹ and $q_0 = 0.15$, respectively.

